

On the Velocity of the TE-polarized Light Wave to Propagate through an Uniform Dielectric Layer

N.L. Chuprikov*

Tomsk State Pedagogical University, 634041, Tomsk, Russia

Abstract

We present a new model of scattering the plane TE-polarized light wave on an uniform dielectric layer. This wave is shown to split uniquely into two causally evolved components to describe alternative subprocesses (transmission and reflection) in all spatial regions. Either component has one incoming and one outgoing waves, joined at the midpoints of the layer with keeping the continuity of the complex-valued electrical field and the energy current density. This model, unlike the conventional one, predicts a subluminal energy transfer through the layer in the regime of a frustrated total internal reflection (FTIR).

Keywords: Hartman paradox, tunneling velocity, energy, layered structure, FTIR

1. Introduction

Scattering the plane monochromatic light wave on an uniform dielectric layer is one of the simplest scattering problems in classical electrodynamics, and, at first glance, its well known model presented in [1] (further named the conventional electro-dynamical model of tunneling (CEMT)) represents its maximally complete and consistent description. However, studying the temporal aspects of this process shows that this is not the case. Like the conventional quantum-mechanical model of tunneling (CQMT) [2, 3, 4, 5, 6] to predict the anomalously short tunneling time for a particle tunneling through an opaque potential barrier, the CEMT does it for the light wave to propagate, under the condition of frustrated total internal reflection (FTIR), through the air gap in the structure with doubled prisms [7] – the Hartman effect.

In quantum mechanics the origin of this paradoxical effect and all difficulties to arise in studying the temporal aspects of tunneling is usually associated (see [6]) with the absence in quantum theory of the Hermitian time operator. However, in classical electrodynamics this explanation is clearly irrelevant and, thus, it does not reflect the real origin of this effect – this origin must be common for both these theories.

Some authors (see, e.g., [8, 9]) consider that the tunneling velocity concept applies only to *localized* wave packets, and the above paradoxical effect is but the result of ignoring this restriction. Others (see, e.g., [9]), following Sommerfeld, narrow the domain of applicability of this concept to *discontinuous* wave packets. They treat the tunneling velocity as the signal (or information) velocity to describe the propagation of the wave-packet's discontinuities.

However, the last two explanations are unacceptable too. Firstly, in the tunneling phenomenon "... an incoming peak or

centroid does not, in any obvious physically causative sense, turns into an outgoing peak or centroid..." [4, 5]. And this concerns not only the wave-packet's centroid but also its discontinuities, if they exist. Secondly, physics deals with the energy or matter transfer, rather than with the information transfer. Thus, above all a physicist has to take into account that the plane light wave transfers energy, whether it propagates in the infinite uniform transparent medium or tunnels through a layered dissipative structure. Therefore, the basic velocity concept to characterize the energy transfer – the velocity of energy flow – must be applicable to tunneling without restrictions.

Of course, this needs the individual description of the transmitted and reverberative components of the original light wave in all spatial regions. However, just this is beyond the scope of the CEMT. This model does not allow any division of the incident light wave into these to-be-transmitted and to-be-reflected components, what makes impossible a correct definition of the velocity of transferring the electromagnetic energy through the layer, within the CEMT. And just this feature of this model is the origin of all paradoxes to surround tunneling at present.

Thus, instead of producing new and new concepts of the tunneling velocity and tunneling time, it is necessary to revise the CEMT in order to fulfill this requirement, and to apply the fundamental concept of the energy velocity to studying the temporal aspects of tunneling. For a *quantum* tunneling this program was realized in the approach [10, 11] (see also [12, 13]). The aim of this paper is to adapt it to scattering the plane TE-polarized light wave on an uniform dielectric layer.

2. Setting the problem

Let us consider two uniform nonmagnetic ($\mu = 1$) media of dielectric permittivities ϵ_0 and ϵ : the medium of refractive index n ($n = \sqrt{\epsilon}$) fills the interval $[0, d]$ on the axis OZ , and the back-ground medium of refractive index n_0 ($n_0 = \sqrt{\epsilon_0}$) fills the spa-

*Corresponding author. Tel.: +7 382 244 6826; fax: +7 382 244 6826
Email address: chn1@tspu.edu.ru (N.L. Chuprikov)

tial regions laying outside this interval; $n, n_0 \geq 1$; $n \neq n_0$. Both these media are assumed to be transparent and non-dispersive.

Let the plane light TE wave fall from the left on the interface $z = 0$, provided that its wave vector lays in the plane YZ and the angle between this vector and the axis OZ is θ . In this case only one projection, E_x , of an electrical field and two projections, H_y and H_z , of a magnetic field are nonzero. To exploit the analogy between the optical and quantum tunneling problems, it is suitable to write down these quantities to obey the same wave equation in the complex form (see [1]).

Since the structure investigated is nonuniform only in the z -direction, we have

$$E_x = U(z)e^{i\chi}, \quad H_y = V(z)e^{i\chi}, \quad H_z = W(z)e^{i\chi};$$

$$\chi = kn_{0,y}y - \omega t, \quad n_{0,y} = n_0 \sin \theta, \quad k = \omega/c;$$

c is the speed of light in vacuum. When these complex solutions are known the above searched-for (real) projections of electrical and magnetic fields are simply $\Re(Ue^{i\chi})$, $\Re(Ve^{i\chi})$ and $\Re(We^{i\chi})$. For nonlinear characteristics – the energy density w and Poynting vector \mathbf{S} – of the TE wave to propagate in the medium of dielectric permittivity ϵ we have

$$w = w^{(0)} + w^{(t)}, \quad \mathbf{S} = \mathbf{S}^{(0)} + \mathbf{S}^{(t)}, \quad (1)$$

$$w^{(0)} = \frac{1}{16\pi} (\epsilon|U|^2 + |V|^2 + |W|^2); \quad (2)$$

$$w^{(t)} = \frac{1}{16\pi} \Re \left[(\epsilon U^2 + V^2 + W^2) e^{2i\chi} \right];$$

$$S_x^{(0)} = S_x^{(t)} = 0;$$

$$S_y^{(0)} = -\frac{c}{8\pi} \Re(U^* W); \quad S_z^{(0)} = \frac{c}{8\pi} \Re(U^* V); \quad (3)$$

$$S_y^{(t)} = -\frac{c}{8\pi} \Re(UW e^{2i\chi}); \quad S_z^{(t)} = \frac{c}{8\pi} \Re(UV e^{2i\chi}).$$

Since the functions V and W are connected to U by the relations (see [1])

$$V(z) = -iU'(z)/k, \quad W(z) = -U(z)n_{0,y}, \quad (4)$$

solving the problem is reduced to finding the function $U(z)$; hereinafter the prime denotes the derivative on z . In particular, outside and inside the interval $[0, d]$, the initial (three-dimensional) wave equation for E_x is reduced, respectively, to the one-dimensional equations for the function $U(z)$,

$$U'' + k^2 n_{0,z}^2 U = 0, \quad U'' + k^2 (n^2 - n_{0,y}^2) U = 0; \quad (5)$$

where $n_{0,z} = n_0 \cos \theta$. At the interfaces $z = 0$ and $z = d$ the function $U(z)$ and its first derivative $U'(z)$ must be continuous. This follows from the boundary conditions for the tangential projections E_x , H_y and for orthogonal projection H_z , as well as from the relations (4).

Note that in the case of a plane (monochromatic) light wave, apart from the conservation law for the energy of electromagnetic field, which follows from the continuity equation

$$\frac{\partial w}{\partial t} + \nabla \mathbf{S} = 0,$$

we have also the conservation law

$$S_z^{(0)} = \frac{c}{8\pi k} \Im(U^* U') = \text{const}. \quad (6)$$

$S_z^{(0)}$ is the analog to the probability current density in the one-dimensional quantum stationary scattering problem.

Let us write down the solutions to Eqs. (5), making use of the notations of the paper [12]. In the region $z \leq 0$, there are incident and reflected waves

$$U(z) = \exp(ikn_{0,z}z) + b_{out}(k) \exp(-ikn_{0,z}z); \quad (7)$$

in the region $z > d$ there is a transmitted wave

$$U(z) = a_{out}(k) \exp[ikn_{0,z}(z - d)]; \quad (8)$$

inside the layer, for $0 \leq z \leq d$,

$$U(z) = A_f G_1(x - z_c; k) + B_f G_2(z - z_c; k); \quad (9)$$

$$a_{out} = \frac{1}{2} \left(\frac{Q}{Q^*} - \frac{P}{P^*} \right), \quad b_{out} = -\frac{1}{2} \left(\frac{Q}{Q^*} + \frac{P}{P^*} \right);$$

$$A_f = -\frac{P^*}{\kappa} a_{out}, \quad B_f = \frac{Q^*}{\kappa} a_{out}; \quad z_c = \frac{d}{2}; \quad (10)$$

$$Q = [G_1'(z) + ikG_1(z)]_{z=z_c}; \quad P = [G_2'(z) + ikG_2(z)]_{z=z_c};$$

if $n_{0,y} \leq n$, then

$$G_1 = \sin(\kappa z), \quad G_2 = \cos(\kappa z), \quad \kappa = k \sqrt{n^2 - n_{0,y}^2};$$

in the case of FTIR, i.e., when $n_{0,y} > n$

$$G_1 = \sinh(\tilde{\kappa} z), \quad G_2 = \cosh(\tilde{\kappa} z), \quad \tilde{\kappa} = k \sqrt{n_{0,y}^2 - n^2}.$$

Here $|a_{out}|^2 = T$ is the transmission coefficient, $|b_{out}|^2 = R$ is the reflection coefficient; $T + R = 1$.

Taking into account the relations (2) and (3) for $w^{(0)}$, $S_y^{(0)}$ and $S_z^{(0)}$, we obtain

$$w^{(0)}(z) = \frac{1}{16\pi} \left[(n^2 + n_{0,y}^2) |U(z)|^2 + \frac{|U'(z)|^2}{k^2} \right],$$

$$S_y^{(0)} = \frac{cn_{0,y}}{8\pi} |U|^2, \quad S_z^{(0)} = \frac{c}{8\pi k} \Im(U^* U') = \frac{cn_{0,z}}{8\pi} T. \quad (11)$$

3. The TE wave as the superposition of two components, transmitted and reverberative

As in the quantum case (see [10, 11]), for any value of k there is a unique pair of functions $U_{tr}(z)$ and $U_{ref}(z)$ which obey the equation

$$U_{tr}(z) + U_{ref}(z) = U(z)$$

as well as possess the following properties: (a) either function unlike $U(z)$ has one outgoing and one incoming wave; (b) the outgoing wave of $U_{tr}(z)$ coincides with the transmitted wave, and that of $U_{ref}(z)$ coincides with the reflected one; (c) the incoming wave of either wave function is causally connected at the plane $z = z_c$ to the corresponding outgoing one – the

complex-valued functions $U_{tr}(z)$ and $U_{ref}(z)$ as well as the corresponding energy current densities are continuous at this plane (but the first derivative of either function is discontinuous here).

For $z \leq 0$

$$U_{tr}(z) = A_{tr}^{in} e^{ikn_{0,z}z} \quad (12)$$

$$U_{ref}(z) = A_{ref}^{in} e^{ikn_{0,z}z} + b_{out}(k) e^{-ikn_{0,z}z};$$

for $0 \leq z \leq z_c$,

$$U_{tr}(z) = D_{tr} G_1(z - z_c; k) + B_f G_2(z - z_c; k) \quad (13)$$

$$U_{ref}(z) = D_{ref} G_1(z - z_c; k);$$

for $z > z_c$

$$U_{tr}(z) \equiv U(z), \quad U_{ref} \equiv 0; \quad (14)$$

$$D_{tr} = -\frac{PQ^*}{P^*Q} A_f, \quad D_{ref} = \frac{1}{K} (PA_{ref}^{in} + P^* b_{out}); \quad (15)$$

$$A_{tr}^{in} = a_{out}(a_{out}^* - b_{out}^*), \quad A_{ref}^{in} = b_{out}^*(a_{out} + b_{out}). \quad (16)$$

As is seen, the found TE waves to describe the transmitted and reflected TE components in all spatial regions possess the following properties. Firstly, not only $A_{tr}^{in} + A_{ref}^{in} = 1$, but also $|A_{tr}^{in}|^2 + |A_{ref}^{in}|^2 = 1$. Secondly, the reflected TE component does not cross the plane $z = z_c$. Thirdly, despite the fact that the derivative $U'_{tr}(z)$ is discontinuous at the plane $z = z_c$, its absolute value $|U'_{tr}(z)|$ is continuous here, because

$$|U_{tr}(z_c - z)| = |U_{tr}(z - z_c)|, \quad |U'_{tr}(z_c - z)| = |U'_{tr}(z - z_c)|. \quad (17)$$

These relations follow from the equality $\Re(D_{tr} B_f^*) = \Re(A_f B_f^*)$ which follows, in its turn, from Exps. (10) and (15).

All this means that for the transmitted TE component the real fields E_x^{tr} and H_y^{tr} , as well as the energy density w^{tr} and the Poynting vector \mathbf{S}^{tr} , are continuous at the plane $z = z_c$:

$$\mathbf{S}^{tr} = (0, S_y^{tr}, S_z^{tr}); \quad S_y^{tr} = \frac{cn_{0,y}}{8\pi} |U_{tr}|^2, \quad S_z^{tr} = S_z^{(0)}; \quad (18)$$

$$w^{tr}(z) = \frac{1}{16\pi} \left[(n^2 + n_{0,y}^2) |U_{tr}(z)|^2 + \frac{|U'_{tr}(z)|^2}{k^2} \right].$$

But the real projection H_z^{tr} is discontinuous at this plane.

So, the light wave splits uniquely into two causally evolving components, transmitted and reverberative. Now, when each component is known in all spatial regions, we can proceed to studying the temporal aspects of this scattering process.

4. Transmission and reflection dwell times

The velocity $\mathbf{v}^{tr}(z)$ ($\mathbf{v}^{tr} = (0, v_y^{tr}, v_z^{tr})$) of the light component to propagate through the layer is introduced, in our approach, as the ratio of the Poynting vector to the energy density at the point z (see Exps. (18)): $\mathbf{v}^{tr}(z) = \mathbf{S}^{tr}(z)/w^{tr}(z)$. Thus, the time τ_D^{tr} to describe the duration of the transmission of the light wave through the layer can be defined as follows

$$\tau_D^{tr} = \int_0^d \frac{dz}{v_z^{tr}(z)} = \frac{1}{S_z^{tr}} \int_0^d w^{tr}(z) dz \quad (19)$$

hereinafter, this quantity will be referred to as the transmission dwell time.

Note that the CEMT deals with the Buttiker dwell time τ_D ,

$$\tau_D = \frac{1}{I_{inc}} \int_0^d w^{(0)}(z) dz, \quad I_{inc} = \frac{cn_{0,z}}{8\pi},$$

which does not distinguish between the to-be-transmitted and to-be-reflected components of the incident light wave. This fully concerns also the so called "group tunneling time" t_{gS} (see [14] and references therein),

$$t_{gS} = \frac{1}{S_z^{(0)}} \int_0^d w^{(0)}(z) dz. \quad (20)$$

Despite different normalization, this quantity has no relation to tunneling, because, like τ_D , it is defined via $w^{(0)}(z)$.

Then, with taking into account (7)-(9) and (12)-(16), for the transmission time we obtain the following expressions. For $n_{0,y} \leq n$

$$\tau_D^{tr} = \frac{k^2}{4k^3 cn_{0,z}} \left[(n^2 - n_0^2) n_{0,y}^2 \sin(2kd) + 2n^2 (n^2 + n_{0,z}^2 - n_{0,y}^2) kd \right]; \quad (21)$$

for $n_{0,y} > n$ (the FTIR case)

$$\tau_D^{tr} = \frac{k^2}{4k^3 cn_{0,z}} \left[(n_0^2 - n^2) n_{0,y}^2 \sinh(2\tilde{k}d) - 2n^2 (n^2 + n_{0,z}^2 - n_{0,y}^2) \tilde{k}d \right]. \quad (22)$$

Figs. 1 and 2 show the dependence τ_D^{tr}/τ_{free} on kd for the case when one medium is vacuum, and another is glass; $\tau_{free} = d/c$. As it follows from Exp. (22) (see also the curve 4 on Fig. 2, obtained for $n_0 = 1, 5$ and $n = 1$), in the case of FTIR ($\theta > 41, 8^\circ$) this quantity exponentially increases when $kd \rightarrow \infty$.

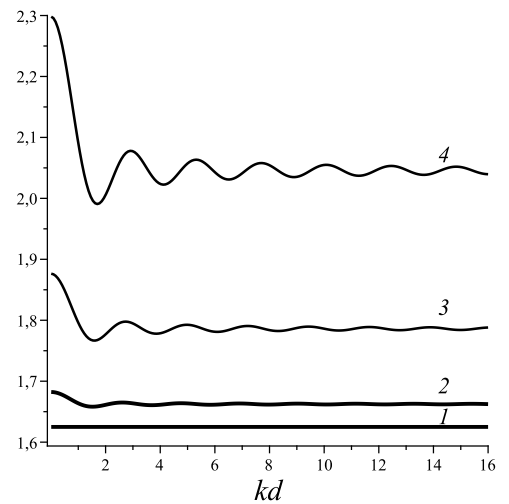


Figure 1: The dependence of τ_D^{tr}/τ_{free} on kd for $n_0 = 1$ and $n = 1, 5$: (1) $\theta = 0^\circ$; (2) $\theta = 15^\circ$; (3) $\theta = 30^\circ$; (4) $\theta = 45^\circ$.

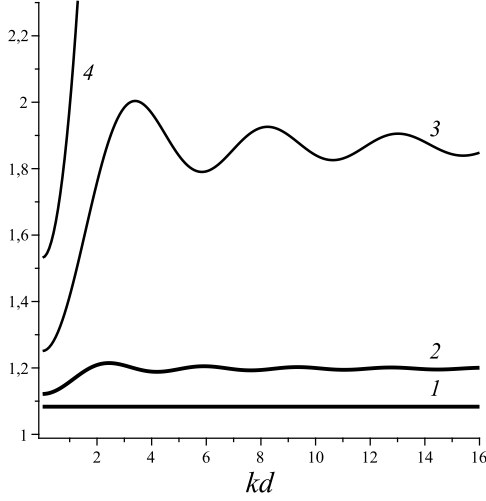


Figure 2: The dependence of $\tau_D^{tr}/\tau_{free}^{tr}$ on kd for $n_0 = 1, 5$ and $n = 1$; the values of the angle θ are the same as for Fig. 1.

When $n_{0,y} \leq n$ the transmission velocity does not exceed c too (see Fig. 1). As it follows from (21), in the limit $kd \rightarrow \infty$

$$\frac{\tau_D^{tr}}{\tau_{free}^{tr}} = \frac{\kappa^2 + k^2 n_{0,z}^2}{2k n_{0,z}} \cdot \frac{n^2}{\sqrt{n^2 - n_{0,y}^2}} \geq 1.$$

Note that τ_D^{tr} does not yield a full information about the velocity of the energy propagation inside the layer, since τ_D^{tr} depends only on the z -projection v_z^{tr} . Therefore a more detailed analysis of this question is done in Section 5.

The reflection dwell time τ_D^{ref} is defined similarly –

$$\tau_D^{ref} = \frac{1}{S_z^{ref}} \int_0^{z_c} w^{ref}(z) dz; \quad S_z^{ref} = \frac{c n_{0,z}}{8\pi} R,$$

$$w^{ref}(z) = \frac{1}{16\pi} \left[(n^2 + n_{0,y}^2) |U_{ref}(z)|^2 + \frac{|U'_{ref}(z)|^2}{k^2} \right].$$

For $n_{0,y} \leq n$, with considering Exps. (12)-(16), we obtain

$$\tau_D^{ref} = \frac{2n_{0,z}}{c\kappa} \frac{n^2 kd - n_{0,y}^2 \sin(kd)}{(n^2 - n_0^2) \cos(kd) + n^2 + n_{0,z}^2 - n_{0,y}^2}; \quad (23)$$

for $n_{0,y} > n$

$$\tau_D^{ref} = \frac{2n_{0,z}}{c\tilde{\kappa}} \frac{n_{0,y}^2 \sinh(\tilde{\kappa}d) - n^2 \tilde{\kappa}d}{(n_0^2 - n^2) \cosh(\tilde{\kappa}d) - (n^2 + n_{0,z}^2 - n_{0,y}^2)}.$$

From Exps. (23) it follows that, under the conditions of FTIR, the function $\tau_D^{ref}(d)$ saturates in the limit $d \rightarrow \infty$. However, this fact does not say that we deal with the Hartman effect, because the reflection time depends not only on the velocity of the reverberative TE-component, but also on the depth of its penetration into the layer. The above fact means simply that in the case of FTIR this depth tends to some fixed value when $d \rightarrow \infty$.

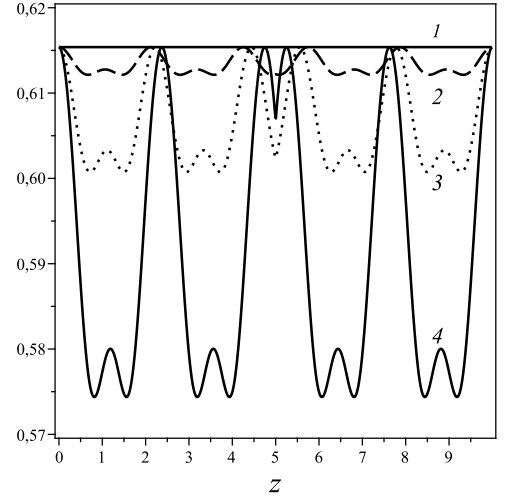


Figure 3: The dependence v^{tr}/c on z for $n_0 = 1$ and $n = 1, 5$; $kd = 10$; the values of the angle θ are the same as for Fig. 1.

5. On the velocity of the energy transfer

A detailed analysis of the velocity of the energy transfer for the light component to pass through the layer has been carried out by the example of the above two media – vacuum and glass. Figs. 3-5 present numerical results obtained for the case when the interval $[0, d]$ is filled with glass. Fig. 3 shows the function $v^{tr}(z) = |\mathbf{v}^{tr}(z)|$ within the layer. Fig. 4 displays the z -dependence of the angle Θ ($\Theta = \arctan(S_y^{tr}/S_z^{tr})$) to characterize the direction of propagation of the transmitted TE component.

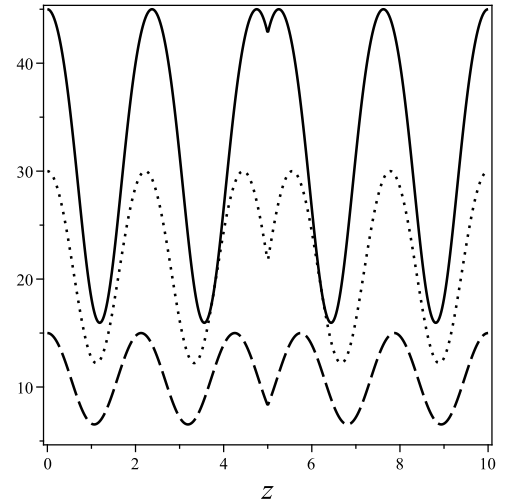


Figure 4: The dependence of the angle Θ on z for the same parameters as for Fig. 3.

As is seen from Figs. 3 and 4, both the functions – $v^{tr}(z)$ and $\Theta(z)$ – reach their maximal values on the set of points, which includes the boundary points $z = 0$ and $z = d$. When θ increases,

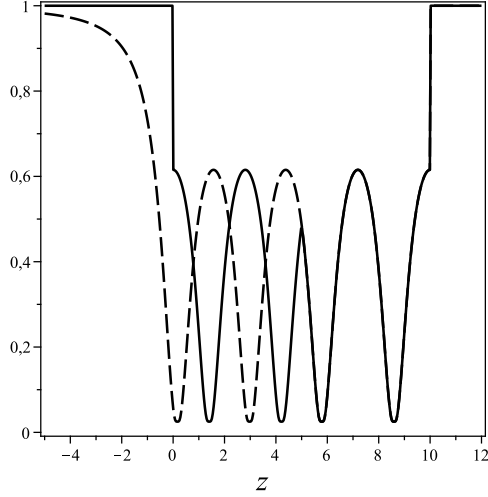


Figure 5: The functions $v^{tr}(z)/c$ (firm line) and $v^{full}(z)/c$ (dashed line) for $\theta = 89, 1^\circ$; the values of remaining parameters are the same as for Fig. 3.

these functions vary more rapidly. In this case, $\Theta(z) \leq \theta$ for $n_0 < n$.

It should be noted that the refraction angle, $\Theta_\infty(\theta)$, to characterize scattering the plane light wave on the *semi-infinite* dielectric medium has no direct relation to the process under study, where this dielectric fills the layer of a *finite* width. For a given θ the function $\Theta(z)$ oscillates, inside the layer, around the value which is approximately equal to $\Theta_\infty(\theta)$.

In the limit $\theta \rightarrow 90^\circ$, the function $v^{tr}(z)$ tends to zero at the points of minimum. This is seen from the numerical results presented on Fig. 3, as well as on Fig. 5, where, in addition to $v^{tr}(z)$, we show also the function $v^{full}(z)$; $v^{full}(z) = |\mathbf{v}^{full}(z)|$; $\mathbf{v}^{full}(z) = \mathbf{S}^{(0)}/w^{(0)}(z)$. At the point $z = 0$ this function like $v^{tr}(z)$ is discontinuous, but its discontinuity is so small in this case that it is unapparent on the figure.

Fig. 5 shows explicitly the principal difference between the behaviour of the functions $v^{tr}(z)$ and $v^{full}(z)$ near the interfaces $z = 0$ and $z = d$. Due to (17) $\mathbf{v}^{tr}(z_c - z) = \mathbf{v}^{tr}(z - z_c)$. However, the "velocity" $\mathbf{v}^{full}(z)$ to underlie the concept of the "group tunneling time" (20), does not obey this requirement! This fact presents one more argument in favor of our approach.

Indeed, in the symmetrical structure to consist of transparent uniform media, all reflection symmetric points are physically equivalent. Thus, the tunneling velocity must represent the even function of $z - z_c$. The reverberative light component to exist only in the left half of the interval $[0, d]$ must not affect the *tunneling* velocity.

Of importance is to stress that $v^{tr}(z) = c/n_0$ outside the interval $[0, d]$. Inside this interval the function $v^{tr}(z)$ varies. However its values do not exceed here the limiting velocity c . For $n > n_0$ the velocity $v^{tr}(z)$ takes its maximal value at those points z where $\sin(\kappa z) = 0$. This set is always nonempty, as it contains the boundary points $z = 0$ and $z = d$. At any point of this set

$$v^{tr} = v_{max}^{(1)} = \frac{c}{n} \cdot \frac{2n_0n}{n_0^2 + n^2} < \frac{c}{n}.$$

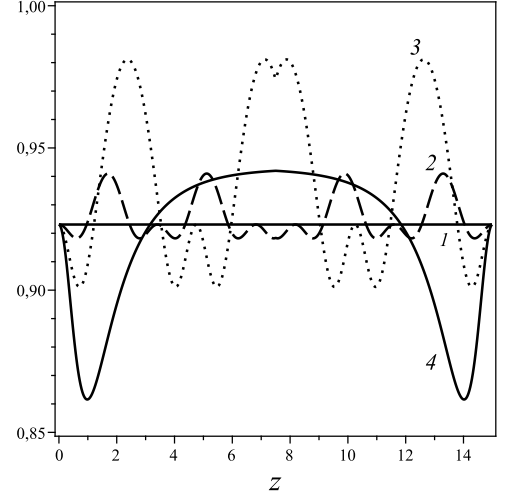


Figure 6: The dependence of v^{tr} on z for $n_0 = 1, 5$ and $n = 1$; $kd = 10$; the values of the angle θ are the same as for Fig. 1.

Figs. 6-8 present numerical results for the case when, in the considered structure, glass and vacuum traded places. Figs. 6 and 7 show, respectively, the functions $v^{tr}(z)$ and $\Theta(z)$. Fig. 8 shows the functions $v_z^{tr}(z)$ and $v_z^{full}(z)$ for their comparison in the case $n < n_{0,y}$.

Note that for $n_0 > n \geq n_{0,y}$ the velocity v^{tr} takes maximal value at those points z where $\cos(\kappa z) = 0$:

$$v^{tr} = v_{max}^{(2)} = \frac{c}{n} \cdot \frac{2k^2 n_{0,z} n \sqrt{\kappa^4 + k^4 n_{0,y}^2 n_{0,z}^2}}{k^4 n_{0,z}^2 n^2 + (\kappa^4 + k^4 n_{0,y}^2 n_{0,z}^2)} \leq \frac{c}{n}.$$

If $n = n_{0,y}$, then the function $v^{tr}(z)$ reaches the maximal value c/n at the point $z = z_c$. This is the only case when the velocity of light in the medium, fitting the finite layer $[0, d]$, approaches its velocity in the same medium, but fitting the infinite space.

In the case of FTIR, the maximal value $v^{tr}(z_c)$ diminishes when the angle θ increases; if θ exceeds some critical value, the function $v^{tr}(z)$ reaches its maximal value $v_{max}^{(1)}$ at the boundary points $z = 0$ and $z = d$. As regards the point z_c , in the limit $\theta \rightarrow 90^\circ$, $v^{tr}(z_c) = c/n_0$ (see Fig. 8). When $n_0 > n$ the inequality $\Theta(z) \geq \theta$ holds (see Fig. 7).

6. Conclusion

A new model of scattering the plane TE-polarized light wave on the uniform dielectric layer has been developed. It is shown that this wave can be uniquely presented, in all spatial regions, as the superposition of two causally evolved transmitted and reverberative components. Unlike the original light wave either component possesses one incoming and one outgoing waves, joined on the plane $z = z_c$ with keeping the continuity of such quantities as the energy density, the density of the energy flow, the (real) electrical field and the y-th projection of the (real) magnetic field. The z-th projection of the (real) magnetic field

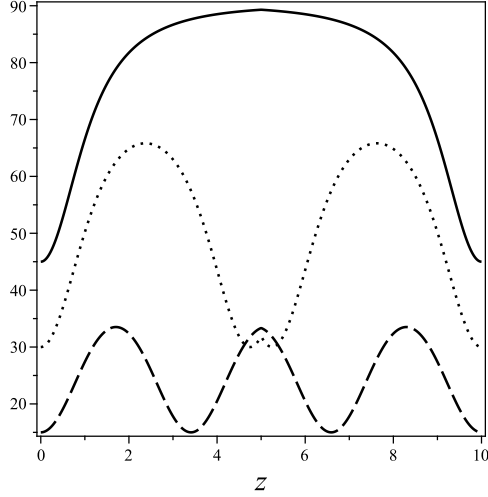


Figure 7: The dependence of the angle Θ on z for the same parameters as for Fig. 6.

for either subprocess is discontinuous at this plane (however, their sum is continuous here).

Within this approach, the concept of the transmission velocity can be consistently introduced as the velocity of the energy transfer, via the Poynting vector and energy density to describe the transmitted component. Unlike the existing CEMT's concepts, ours obeys two important requirements: it does not lead to the Hartman effect in the case of FTIR; it represents the even function of $z - z_c$ for the structure to possess the mirror symmetry, with the symmetry plane $z = z_c$.

Of importance is that the present model is applicable to scattering the plane electromagnetic wave on a layered structure with dispersion and dissipation.

This work has been partially financed by the Programm of supporting the leading scientific schools of RF (grant No 224.2012.2).

References

- [1] M. Born, E. Volf, Principles of Optics, Pregamon Press, Oxford-London-Edinburg-New York, (1964) . 721.
- [2] J.P. Falck, E.H. Hauge, Phys. Rev. B 38 (1988) 3287.
- [3] C.A.A. de Carvalho, H.M. Nussenzveig, Physics Reports 364 (2002) 83.
- [4] M. Buttiker and R. Landauer, Phys. Rev. Lett. 49 (1982) 1739.
- [5] R. Landauer and Th. Martin, Rev. Mod. Phys. 66 (1994) 217.
- [6] J.G. Muga, C.R. Leavens, Physics Reports 338 (2000) 353.
- [7] G. Nimtz, Found Phys 41 (2011) 1193.
- [8] J.T. Lunardi and L.A. Manzoni, Phys. Rev. A. 76 (2007) 042111.
- [9] M.V. Davidovich, Phys. Usp. 52 (2009) 415.
- [10] N.L. Chuprikov, Russian Physics Journal 49 (2006) 119.
- [11] N.L. Chuprikov, Russian Physics Journal 49 (2006) 314.
- [12] N.L. Chuprikov, Vestnik of Samara State University. Natural Science Series 67, No 8/1 (2008) 625.
- [13] N.L. Chuprikov, Found. Phys. 41 (2011) 1502.
- [14] Shvartsburg A B Phys. Usp. 50 (2007) 37.

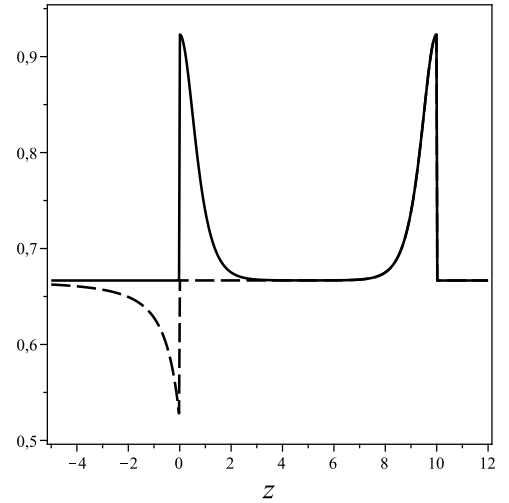


Figure 8: The functions $v^{tr}(z)/c$ (firm line) and $v^{full}(z)/c$ (dashed line) for $\theta = 89, 1^\circ$; the values of remaining parameters are the same as for Fig. 6.